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AGRICULTURAL MEMORANDUM 1036

THE NOCTURNAL BOUNDARY LAYER, WITH REFERENCE TO THE USE OF WIND MACHINES FOR FROST PROTECTION.

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SUMMARY

The purpose of this memorandum is to provide some theoretical and physical insight into the nocturnal boundary layer, with the aim of explaining how a wind machine may or may not be capable of breaking down an inversion over an orchard. The claims of the machines' manufacturers that they can raise the temperature at tree height by half the magnitude of the inversion needs some examination.

It is shown that there is no theoretical obstacle to the machine's ability to adjust the temperature profile significantly, but it is hard to define what the surface temperature rise might be without recourse to experiments. Some thought is also given to the most effective mode of operation for the wind machine:- continuous running or intermittent bursts?

(Note: For readers less familiar with meteorological terms, a Glossary has been included as an appendix.)

INTRODUCTION

At night, the earth's surface radiates in the infra-red part of the electromagnetic spectrum to space, and as a consequence cools. The cold ground, in turn, cools the adjacent air by turbulent and molecular processes. Equally importantly, direct radiative cooling of the air itself occurs from two causes. Firstly, it can radiate upward to outer space, and secondly there will be a radiative loss to the colder ground. (It should be pointed out that the clear air radiation is emitted from water vapour, carbon dioxide, ozone and aerosols.)

During cloud-free nights over land, these processes are responsible for the progressive build up of a stably-stratified layer next to the surface. Development of this surface inversion layer is due to a continuation of the processes outlined above allied to turbulent transport of warmer air downwards, which is cooled by the colder ground. This leads to a cool layer near the ground with residual warmer air aloft from the daytime heating. In this situation the lower atmosphere is in a stable state, as the cold air does not possess any buoyancy, and vertical motion by this means is therefore limited. This is not to say that turbulent motions may not be present, but they occur as a result of shear production. This turbulence is then available to produce a downward flux of sensible heat to the cold surface, and a consequent upward extension of the cooling. Air movement can also be induced by drainage flows in sloping terrain, and can be responsible for a drastic modification of the inversion layer.

The structure of the nocturnal boundary layer will now be examined in greater detail, with reference to how it might be modified to raise the surface temperature.

STRUCTURE OF THE NOCTURNAL INVERSION

We have seen in the Introduction that cooling by direct radiative effects, and turbulent motions of the cold air, can lead to the formation of a stably-stratified layer. The exact proportion in which these two mechanisms contribute to the total cooling is a matter of some scientific debate. André and Mahrt (1982) suggest that they contribute equally to the development of the nocturnal inversion. There does exist a general consensus of opinion that one is more predominant than the other at different levels. Garrat and Brost (1981)

propose a three-layer structure for the nocturnal boundary layer of height, h, in which the lowest, (0.1 h thick), and uppermost (0.2 h thick), layers are dominated by radiative cooling, while the intervening layer is dominated by turbulent cooling. This is based on results from their numerical model, and the exact size of the respective layers is not wholly supported by experimental data, although the general principle is clearly sound. There is general agreement that maximum clear-air radiative cooling occurs at or near the top of the inversion layer, which explains why the inversion layer thickens with time during the night. Of course, this process will also lead to a decrease in stratification, as the upper layers become relatively colder than the layers beneath. In contrast, turbulent heat fluxes act to increase the stratification through strong cooling towards the surface.

What does all this imply for the vertical temperature structure? Well, it is well documented from field experiments, for example, Wangara (Clarke et al, 1971), and Minnesota (Caughey et al, 1979) that on nights of weak winds and sporadic turbulence, an exponentially-shaped potential temperature profile is observed. An idealised form is shown in Figure 1. (Potential temperature is used because it is easier to discuss in thermodynamic and energy considerations.)

Stull (1983) has done a least-squares fit to the Wangara and Koorin (Clarke and Brook, 1979) datasets and produced the following relation,

$$\theta(z) = \theta_o + \Delta\theta_s \; a \exp(-az/H), \qquad \text{(Equation 1)}$$

where $\theta(z)$ is the potential temperature at height z, $\Delta\theta_s$ is the potential temperature departure from θ_o near the surface, a is a constant estimated to be 0.77, and H is a length-scale, approximately equal to one-fifth of the height, h, of the stable layer. θ_o is the potential temperature of the 'residual layer' at the top of the boundary layer, and because it is greater than the surface temperature, $\Delta\theta_s$ is a negative quantity.

ENERGY IMPLICATIONS

The potential energy (P.E.) of the nocturnal boundary layer should decrease as it develops, because the height of the centre of gravity will fall as a consequence of the cooling. Conversely, any upward movement of cold air will result in an increase in P.E. as the height of the centre of gravity then rises.

The inference is that in order for a stable inversion layer to be modified to an isothermal layer, some energy will have to be put into the layer to bring about this transformation. An operating wind machine will generate turbulent kinetic energy (T.K.E.), which will be used to transport cold air upwards and warmer air downwards before being converted to P.E., as the layer reaches a higher overall energy state.

It seems reasonable to suppose that in order for a wind machine to achieve its aim of producing an isothermal layer from an inversion layer, it will have to provide at least an amount of energy equal to the differences in P.E. between the two states. Therefore, if this difference can be calculated, it should be possible to say whether or not a wind machine of a given power can break up an inversion layer.

The P.E. per unit area of a non-adiabatic layer is given by,

$$\text{P.E.} = \int_0^{z_R} \rho_o g \frac{\Delta\theta}{\theta_o} z \, dz, \qquad \text{(Equation 2)}$$

where ρ_o = average density
g = gravitational constant
$\Delta\theta = \theta(z) - \theta_o$
Z_R = the height at which $\theta(z)$ is within 2% of θ_o

This is equivalent to saying that the P.E. of the layer is proportional to the area under the θ against z curve. For the whole nocturnal boundary layer this is not too difficult to calculate, as equation 1 may be substituted into equation 2 to give,

$$P.E. = \frac{\rho_o g}{\theta_o} \int_o^{z_R} \Delta\theta_s \, a \exp(-az/H) \, z \, dz \quad \text{(Equation 3)}$$

Integrating, and assuming that the reference height (z_R) is large, gives,

$$P.E. = \frac{\rho_o g}{\theta_o} (\Delta\theta_s) \frac{H^2}{a} \quad \text{(Equation 4)}$$

However, this expression is not directly useful in the specific case of frost protection, as the constants H and a have not been exactly determined, and more importantly the wind machine's influence will probably not extend to the residual layer where $\theta(z) \sim \theta_o$. Because of this, it is more appropriate to idealise the profile further to that shown in Figure 2. The P.E. is then calculated as;

$$P.E. = -\frac{1}{2} \frac{\rho_o g}{\theta_o} (\theta_h - \theta_I) z_I^2 \quad \text{(Equation 5)}$$

The temperature profile after the wind machine has been in operation is more difficult to define, as there are no authoritative datasets available with the possible exception of Medford Valley, Oregon (Bates and Lombard, 1978). Initially, one presumes, the air in the affected layer will be overturned and a mixed-layer, or isothermal, profile will be set up. An isothermal profile is the best that can be achieved without additional heating. The surface temperature, θ_s, that is produced is a matter of speculation, but let us assume for the present that it will indeed be half-way between the temperature at the top of the inversion, and the previous surface temperature. This of course produces a temperature discontinuity at the top of the wind machine's influence in some circumstances, because an isothermal profile will have a straight line of slope equal to approximately 1K per 100m, assuming a dry atmosphere. In theory, then, the result will be a profile as shown in Figure 3, which in time might develop into a profile as depicted in Figure 4, because mixing would take place across the discontinuity.

Using the same reference point as for the example in Figure 2, ie 0_o, and with the temperatures as defined in Figure 3, the P.E. under the initial isothermal profile is given by,

$$\text{P.E.} = -\left[\frac{1}{2}(\theta_A-\theta_M)+(\theta_h-\theta_A)\right] z_w^2 \frac{\rho_o g}{\theta_o} \quad \text{(Equation 6)}$$

Let us now put some appropriate numbers into equations 5 and 6, to see what the magnitude of the energy difference is. Suppose that,

θ_o = 285 K
θ_I = 0°C
θ_h = 5°C
θ_M = 2.5°C
θ_A = 3.0°C
$z_I = z_w$ = 50m
ρ_o = 1.2 kg m^{-3}
g = 9.8 ms^{-2}

Then, i for the inversion, P.E. = -257.9 Jm^{-2}
ii for the isothermal case, P.E. = -232.1 Jm^{-2}

Therefore, in this highly artificial case, the P.E. change is 25.8 Jm^{-2}. Wind machines are claimed to be effective over an area of about 4 hectares, so the total energy input would need to be 1000kJ. On this basis, a typical 120hp, (= 90 kW,) machine should very quickly be able to break down the inversion layer used as an example here - in 11 seconds. Layers with greater values of $(\theta_h-\theta_I)$ will of course require a greater energy input, but would appear to still be well within the capacity of the average wind machine to break down.

It is puzzling that the amount of energy required to bring about this conversion is so small, in view of the size of the various heat fluxes, etc normally present, which are of the order of 20-50 Wm^{-2}. A possible explanation is that only a small amount is needed to bring about the initial change, but thereafter a lot of work needs to be done in order to maintain the new state against the forces seeking to return it to its stratified state. Also, aside from moving air in the vertical, the wind machine will have to move large volumes of air horizontally in order to have an effect over a wide area. This in itself will require significant amounts of kinetic energy. For instance, a volume of air 4 hectares by 50 m deep moving at 2 ms^{-1} will possess kinetic energy of about 5000 kJ.

Certainly, there are flaws in this simplistic energy argument. The wind machine will not be 100% efficient in converting its own power to T.K.E. in the air. Furthermore, the T.K.E. generated will not all be available to transfer heat against the buoyancy forces, and hence for conversion to P.E. The turbulence kinetic energy budget equation neatly explains the processes involved here. There is no virtue in quoting it explicitly, suffice to say that it states that the rate of change of T.K.E. is equal to the sum of mechanical shear production, buoyancy production, dissipation by viscosity, and two minor terms which are of no relevance here, (self-advection and pressure advection). Viscous dissipation of energy in the boundary layer is the principal means of its final destruction. Energy is transferred from larger eddies to smaller ones, until finally the smallest eddies are dissipated by viscosity. The implication, therefore, is that not all the T.K.E. is available to transport the heat vertically against the buoyancy restoring forces. This will be particularly so for wind machines with small propellers. Stull (1983) suggests that 90% of naturally generated T.K.E. is dissipated by viscosity. In the case of wind machines however, more should be available for work because of the short timescales and relatively long length scales involved. It is likely that, even allowing for the effects of viscous dissipation, there should still theoretically be more than enough energy input available to break up the inversion.

DEVELOPMENT OF THE NEW MIXED LAYER WITH TIME

Having established that there is no obvious reason why a wind machine should not be able to significantly modify the vertical temperature profile, the next questions to consider is, what happens after the machine has been operating for some time?

The wind machine is effectively a mixing device (it does not merely draw warm air downwards), and viewed simplistically it is operating in a closed layer, the lower boundary of which is being radiatively cooled at rates of between 0 and, say, 4 K hr^{-1}. The conclusion, therefore is that this idealised layer undergoes an overall cooling, by the same mechanism that turbulent fluxes cause the natural nocturnal boundary layer to cool. The difference being, that in the case of the wind machine, stratification is not increased - for obvious reasons.

Does this apply to the real situation? Well, there is no reason to suppose that it will not behave roughly like this, given continuous radiative cooling, and an absence of horizontal advection. The layer is effectively a closed one in the vertical, since the wind machine has a limited height of influence, and the air within this mixed layer is not buoyant enough to penetrate upwards through the 'ceiling'. There will be some mixing at the top of the layer as the momentum of the generated eddies carries them along, but this will probably be limited. The greatest departure from reality is to view the situation in only one dimension, ie the vertical, and ignore the mixing and diffusive effects in the horizontal. Also, the artificially created downward flux of warmer air is so much more vigorous than any natural turbulent flux, and its buoyancy near the ground may be so great that it is simply not there long enough to effect much heat transfer. However, against that, if the assumption of a closed, well-mixed layer is valid, then sooner or later, all the air will eventually come into contact with either colder air or the ground.

If this principle is accepted, then the temperature profile will change as in Figure 5. In the limiting circumstance the potential temperature at the surface will equal the original surface temperature, θ_I, but this is a rather hypothetical situation. How close θ_M might approach θ_I, and how quickly, is difficult to decide. The theory is too speculative to stretch it towards making quantitative predictions of this nature. However, the possibility of this sort of behaviour occurring in reality prompts the question as to the most sensible mode of operation for these machines:- short bursts or continuous running? If the time taken for the layer to revert to its original profile after the machine has been switched off is short, then continuous running will be the more favourable option. Otherwise, it could be that prolonged use in one night could eventually be self-defeating. This needs to be determined experimentally before a clear answer can emerge.

The assumption of no horizontal advection, it could be argued, is unrealistic. Even with a mean drift of 1 ms^{-1}, air will be moved 300 m in 5 minutes, which means that a very substantial part of the new mixed layer will swiftly be replaced by incoming undisturbed air. Therefore the prolonged use of a wind machine should only be questioned in conditions of complete calm.

It may be of some comfort to the grower to know that is unlikely that by using the wind machine he can exacerbate the frost problem. Even if the mixed layer was cooled completely, the surface temperature is limited to that which would be present under an inversion. Nor can the plant tissue lose heat to the air by forced convection, since at best its temperature will be equal to that of the air, and at worst it will be up to 2°C lower than the air. The temperature difference, therefore, is always in favour of heat transfer from the air to the plant, or none at all, during conditions of net radiative loss.

GENERAL HEAT BUDGET CONSIDERATIONS

The ideas put forward concerning energy exchange in the nocturnal boundary layer should be put into a general perspective. The surface temperature and its cooling rate will be determined by the energy exchange that is present there, which is given by,

$$k \frac{\partial T_s}{\partial t} = R_N + C + LE + G,$$

where k = a constant of proportionality
T_s = the surface temperature (K)
R_N = net radiation flux
C = sensible heat flux
LE = latent heat flux
G = ground heat flux

At night, the net radiation is usually negative, particulary on clear nights when its magnitude can be as high as 100 Wm^{-2}. The sensible heat flux is made up of convective heat exchanges which operate in the direction of the temperature gradient and are forced or free, depending on the wind strength. At night, the surface and the trees can usually only gain heat from sensible heat exchanges. Soil heat flux will also act to warm the surface. The temperature at a depth of say, 10 metres, is a constant 10°C, as it is in long term equilibrium with the atmosphere. At lesser depths, the temperature is also likely to be greater than that at the surface, in conditions relevant to frost

protection. Therefore, heat will always be available for conduction to the surface on winter and spring nights. With the right temperature gradient, this can amount to 50 Wm^{-2}. G is also dependent on the thermal properties of the soil; wet clay for instance has an order of magnitude higher thermal conductivity than dry clay.

The latent heat exchange is always more difficult to quantify, as it is so dependent on the amount of available moisture. However, there is no doubt that it is at least as important a contribution to the heat balance as the other terms. On occasions of dew deposition at the rate of 0.05 mm hr^{-1}, which is realistic for nearly saturated air, the latent heat release is about 35 Wm^{-2}.

It is useful to consider the relative magnitude of the terms involved in the heat budget, in order to appreciate the rapid changes in surface temperature that can and do take place. It is a well documented fact that the near surface temperature rises very quickly on occasions in stable boundary layers. Measurements made by the Meteorological Research Unit, RAF Cardington, and by Cochrane (1984) show this to be a common occurrence. These sharp and pronounced natural rises in surface temperature can be attributed to several causes. The most obvious of these is the overhead passage of cloud. In this event the net radiative loss instantaneously falls to zero, resulting in a positive heat contribution from the ground heat flux at least. Another contribution to warming could arise from large mesoscale 'rolls', which are thought to impinge on the boundary layer, causing temporary disruption to the inversion and raising the sensible heat contribution to the surface energy budget.

The significance of this section is to illustrate the fact that the energy budget at the surface is very finely balanced, and the surface temperature under typical inversions in this country can rise and fall by several degrees quite naturally, without interference by man.

CONCLUSIONS

On still, cloud-free nights it has been shown by several workers, both experimentally and theoretically that an exponentially-shaped potential temperature profile exists. This inversion layer is created by the action of radiative cooling and enhanced by turbulent fluxes, but can easily be disturbed by the passage of cloud, an increase in the mean wind, large-scale motions penetrating the boundary layer, and possibly by latent heat exchanges.

In theory, there is no impediment to a wind machine also bringing about a drastic modification to the temperature profile, by operating as a mixing device. Unfortunately, whilst it is possible to establish that a wind machine can provide more than enough power, in the form of kinetic energy, to produce a well-mixed layer, it is very difficult to predict what the new surface temperature will be. Measurements of the temperature profile before, during and after the use of one of these machines need to be made before any definite conclusion can be made concerning the magnitude of any temperature changes.

There is a possibility that prolonged use of the wind machine during the same calm night will cease to be of any benefit, although no harm can be done over and above what would have occurred without any mixing. Again, this needs to be verified experimentally.

The question of whether wind machines are viable or not for frost protection is therefore a matter of climatology. That is to say, their usefulness is determined by the frequency of suitably strong inversions. Cochrane (1983) has examined this aspect of the problem.

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Any comments or suggestions should be addressed to the author.

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GLOSSARY OF METEOROLOGICAL TERMS

Boundary layer: That part of the atmosphere which is adjacent to the surface. Its depth can vary from 100 m on a winter night to 1 km on a hot summer day.

Inversion: The situation whereby temperature is increasing with height, usually up to a clearly defined height. The layer from the surface up to this height is then described as the inversion layer.

Isothermal layer: A layer in which the temperature is constant with height.

Mesoscale: A length scale used in meteorology to describe disturbance and motions in the atmosphere between 1 km and 100 km in size.

Mesoscale 'rolls': A non-standard term used here to describe large scale roll vortices or eddies which are sometimes prevalent in the lower atmosphere. They are best visualised as large circular motions (in the vertical).

Potential temperature (θ): The exact definition is that temperature which a given sample of air would attain if transferred adiabatically, (ie without loss or gain of heat), to a standard pressure of 1000 mb. It is probably more helpful to the reader to compare Figures 1a and 1b in order to relate potential temperature to temperature. At the surface potential temperature and temperature are similar, and in fact equal to each other if the surface pressure happens to be

1000 mb, but as the height increases, then potential temperature normally becomes the greater of the two. Potential temperature is used because it is more directly related to energy exchanges than conventional temperature.

Stably-stratified layer: A layer associated with inversion conditions, which is stable because buoyant vertical motions are suppressed, and as a consequence unbroken lines of equal temperature can be drawn horizontally, with the coldest air at the bottom.

Well-mixed layer: A layer which has been 'stirred' sufficiently to disrupt stratification and move colder air upwards, but not to the point where an isothermal profile is created.

Figure 1a Idealised exponential profile of potential temperature in the nocturnal boundary layer.

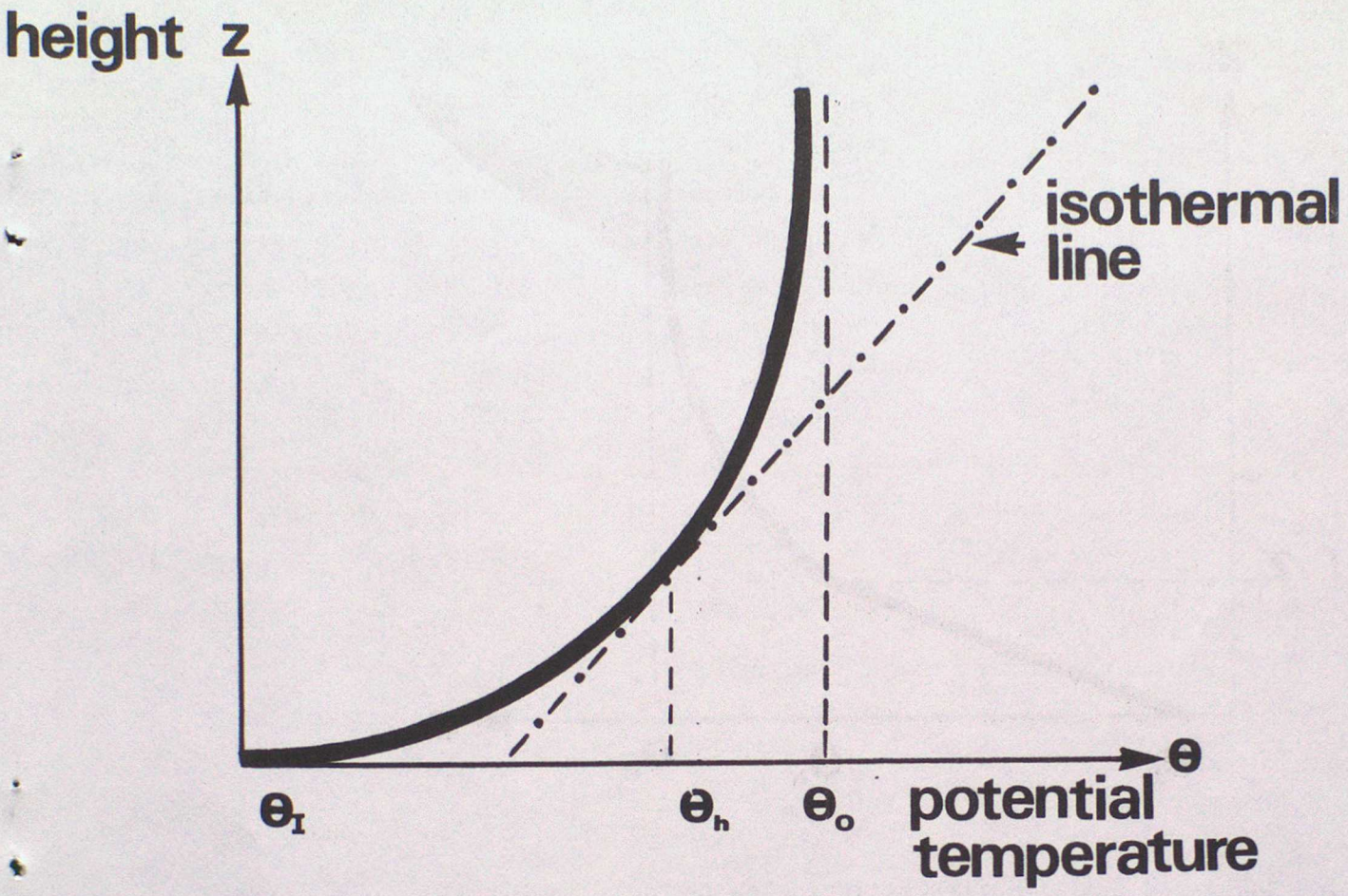

Figure 1b The same profile as above, but against temperature instead of potential temperature.

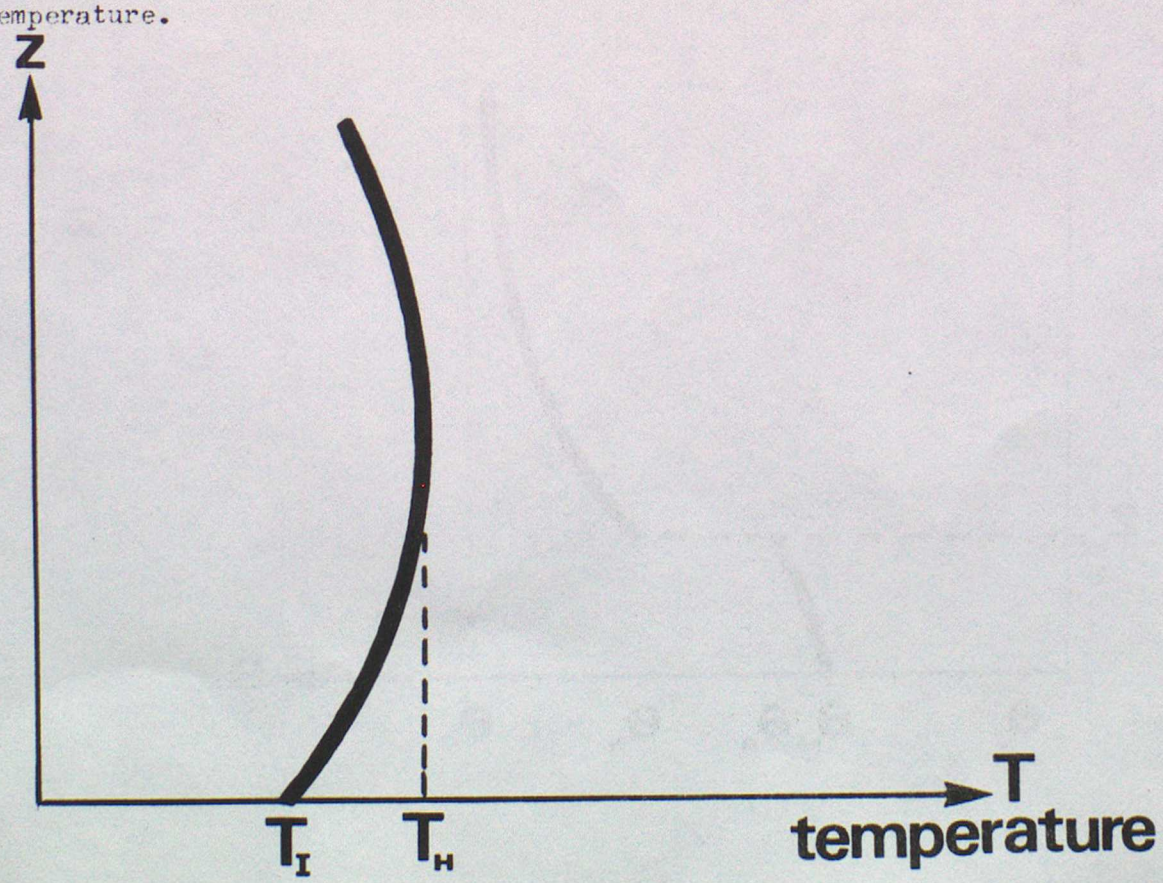

Figure 2. Approximation to the exponential profile.

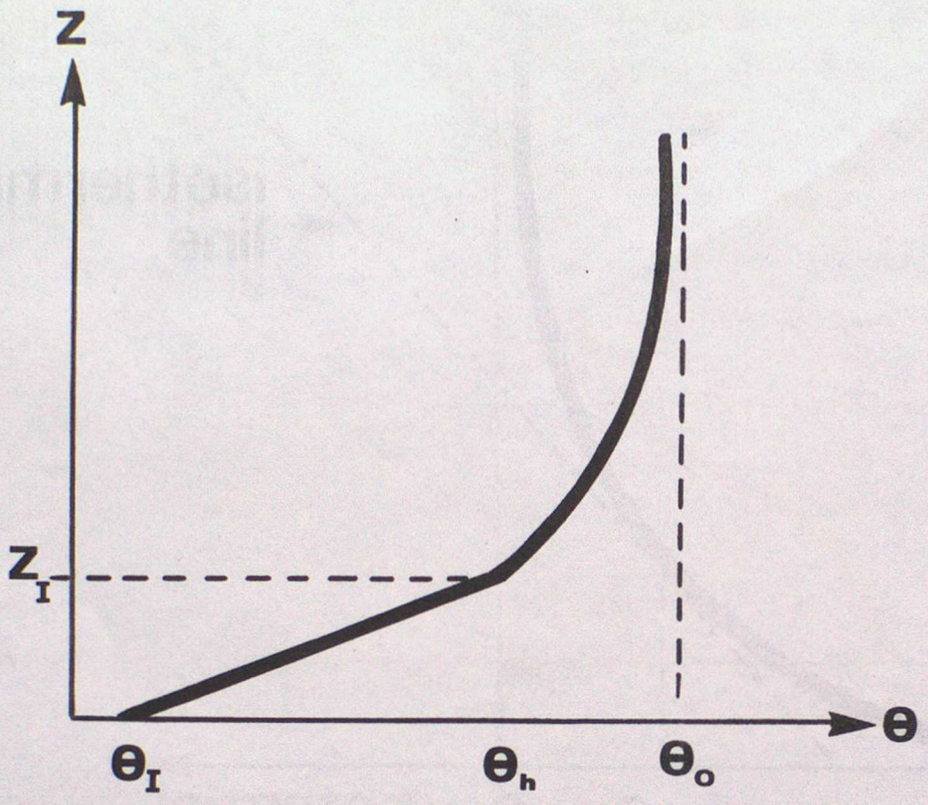

Figure 3. Suggested profile after switching on the wind machine.

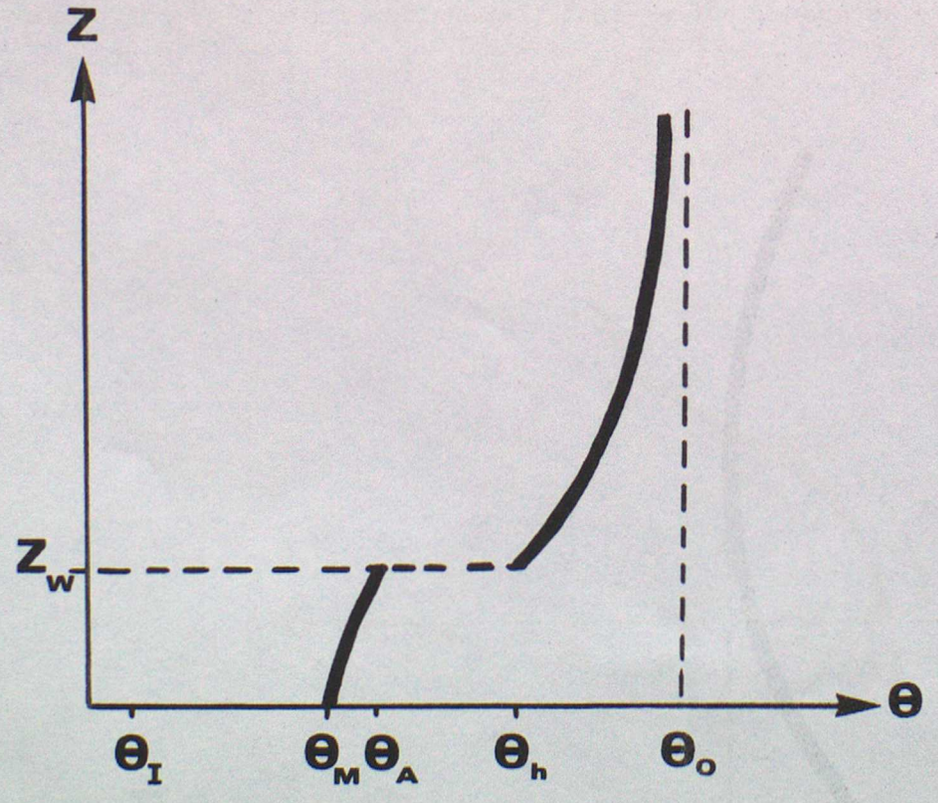

Figure 4. Possible profile after a period of running the wind machine.

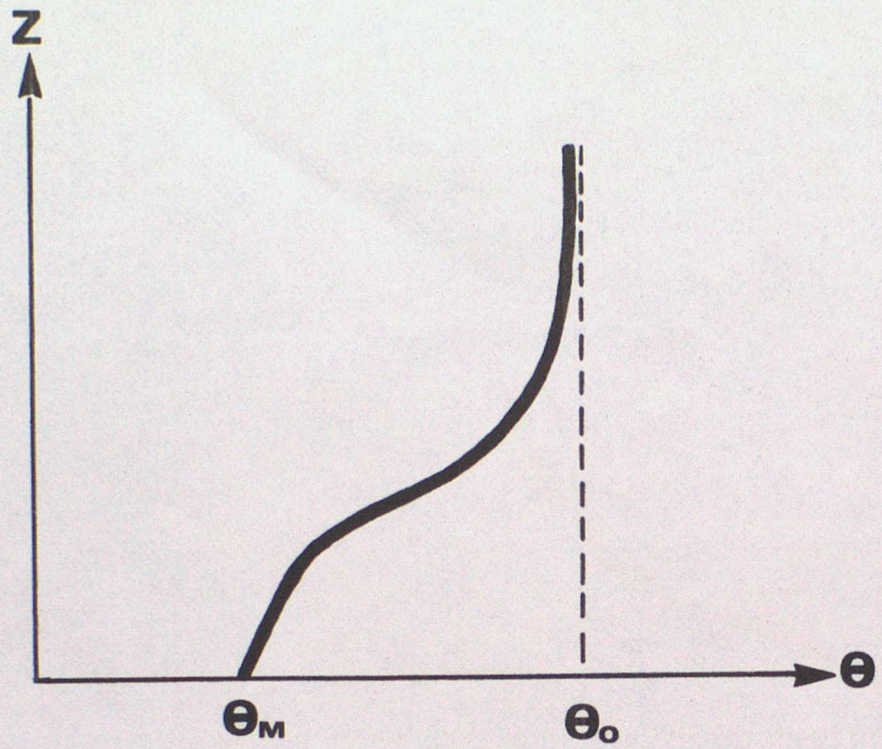

Figure 5. Suggested change of the profile after prolonged wind machine operation.